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Sensitivity to disparity corrugations in peripheral vision

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Abstract

Disparity discrimination thresholds are known to increase with both retinal eccentricity and distance from the horopter. However, little is known about how the detectability of cyclopean gratings varies with retinal position. Thresholds for disparity corrugations were measured as a function of corrugation frequency for different visual eccentricities. Subjects viewed annular displays of random dot stereograms, and judged in which of two intervals a circumferential disparity modulation was present. For any given eccentricity, visual sensitivity to disparity corrugations was bandpass. As eccentricity increased from 3.5 to 21.0°, peak-to-trough thresholds were found to increase, the optimal corrugation frequency for detection decreased, and the upper cutoff corrugation frequency also decreased. The M-Scaling functions of Rovamo and Virsu were used to replot the data in terms of cycles per unit cortical distance. Peak detection frequency was constant at 0.8 cycles per mm of cortex after this rescaling, demonstrating that acuity for disparity modulations is approximately M-scaled beyond the fovea.

Keywords: Stereopsis; Acuity; Eccentricity

1. Introduction

Visual sensitivity to sinusoidal luminance patterns decreases as the retinal locus moves away from the fovea [1–3]. Specifically, the overall contrast sensitivity function is depressed with increasing eccentricity, the peak detection frequency is decreased, and the location of high frequency cut-off is reduced. Rovamo et al. [3] argued that the shape of the contrast sensitivity function (CSF) in the periphery is contingent on the cortical area affected by the stimulus. The function relating a degree of visual angle to the corresponding linear extent of cortical representation is known as the cortical magnification factor. This was initially estimated in humans by Cowey and Rolls [4], based on the data of Brindley and Lewin [5] who measured the position in visual space of the sensations resulting from direct stimulation of the cortex. However, these measurements were limited to a restricted portion of the lower visual field, and more recent estimates rely on the assumption that cortical area is proportional to retinal ganglion cell density [6]. Rovamo et al. [3] demonstrated that if both the spatial frequency and size of the stimulus were scaled by the inverse of the cortical magnification factor then the CSFs at different eccentricities collapse to form a single function.

A series of studies has shown that the detection of sinusoidal disparity modulation has many features in common with the detection of luminance gratings. Tyler [7,8] investigated disparity modulation in line stereograms and showed that corrugation sensitivity function was bandpass, peaking at around 0.4 cpd and could not be perceived above 3 cpd. Tyler [9] first investigated sinusoidal depth variations in random dot displays using the 'method of display mark-up', in which observers viewed a stereogram which varied continuously in horizontal corrugation frequency in one direction and corrugation depth in the perpendicular direction. Subjects were required to mark the boundary where they could no longer see the corrugations. They showed that sensitivity was bandpass and peaked at

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about 0.4 cpd. Similarly, Rogers and Graham [10] showed that the disparity sensitivity function was band-pass with lowest thresholds for corrugations of around 0.3 to 0.5 cpd. Bradshaw and Rogers [11] remeasured the sensitivity function using a method of constant stimuli for corrugations between 0.0125 and 3.2 cpd and found the maximum sensitivity to be at 0.3 cpd, where peak-to-trough thresholds were as low as 2 arc sec. Other similarities with the luminance CSF have also been found, Ioannou et al. [12] (see [13]) showed that disparity sensitivity functions flattened out at supra-threshold disparity modulations in an analogous way to the contrast constancy data reported by Georgeson and Sullivan [14]. Schumer and Ganz [15], Tyler [16] and Cobo-Lewis and Yeh [17] used a masking paradigm to demonstrate the existence of disparity-frequency tuned channels. However, unlike in the detection of luminance gratings, there is a strong anisotropy in the detection of disparity modulation: thresholds for horizontal corrugations are considerably lower than for vertical for most observers [18].

Little is known about disparity sensitivity in peripheral vision; Blakemore [19] demonstrated that depth discrimination thresholds for line targets increase as the stimulus moves away from the fovea. These thresholds increased faster than resolution acuity fell [20]. Richards and Regan [21] used a vertical bar oscillating in depth at 2 Hz to demonstrate that stereo-performance was still present at 20° of eccentricity. Siderov and Harwerth [22] measured the effect of luminance spatial frequency on disparity-thresholds at eccentricities of up to 10° from the fovea. They showed that low spatial frequency depth discrimination was constant with eccentricity, but discrimination for high spatial frequency targets became worse. The only previous study examining sensitivity to disparity corrugations as a function of eccentricity was performed by Tyler [8] who used sinusoidally modulated line stimuli to compare sensitivity to gratings viewed foveally and at 7°. Results showed that both lower and upper limits were unaffected at low corrugation frequencies, but that the peak sensitivity frequency decreased as sensitivity to high frequencies decreased.

In the present experiment, the analogy between luminance gratings and disparity modulations is explored further, by measuring the disparity modulation sensitivity as a function of visual eccentricity.

2. Methods

The stereoscopic stimuli were displayed on a Wheatstone stereoscope consisting of two 21 inch Apple monochrome monitors and viewed via a pair of mirrors mounted at right angles to one another. These monitors were driven by the internal video of an Apple Power Macintosh 7500/100 from which the blue component of the video signal was sent to the left screen, and the red component to the right screen, although the displayed images were always monochrome. For the most eccentric condition, measurements were made using a larger Wheatstone stereoscope consisting of two $70 \times 70°$ screens onto which the images were rear projected. In both cases, the viewing distance was 57 cm with appropriate convergence.

The stimuli consisted of 50% density random dot patterns within an annular aperture and surrounded by a black background. A circumferential disparity modulation was introduced between the images, so that the depth corrugations were radial and similar to the spokes on a bicycle wheel, but with only the portion in the annular aperture visible. A stereogram portraying the radial corrugations is shown in Fig. 1. The spatial frequency of the corrugations and the radius of the annulus were varied between conditions. The width of the annulus was always constant at 3.3°. In an attempt to control for stimulus visibility, the size of dots used in the display was scaled linearly with eccentricity. The use of a high Michelson contrast, together with this scaling ensured that all stimuli were far above luminance contrast detection thresholds.

To gain sufficient disparity resolution, sub-pixel interpolation of the dot boundaries was employed. This makes the assumption that the visual system blurs the individual pixels sufficiently that disparities smaller than pixel size may be represented by adjusting the luminance values appropriately. To prevent subjects detecting the increased blur that is a necessary side-effect of this process, all stimuli were initially blurred with a horizontal '121' operator, which disguised this monocular information. The annulus width was randomly jittered to prevent subjects using the monocular cues that accompany the introduction of disparity.

The small angle assumption was used in generation of the stimuli. Note that because disparity was modulated with respect to a surface lying in a frontal plane, the disparity modulations at large eccentricities were: (i) not symmetric with respect to the Vieth–Müller circle;

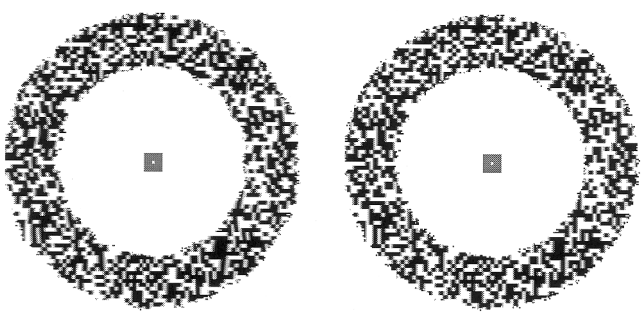

Fig. 1. Example of stimulus. Free fusion reveals a sinusoidal depth pattern. (not to scale).

and (ii) not coincident with the inclined vertical horopter [23]. Nonetheless, the magnitude of disparity modulations required for detection in the periphery was always sufficiently large that the modulations crossed the horopter (see discussion).

There was always an integer number of cycles around the annulus. In addition, there were never fewer than four complete cycles of disparity modulation around the annular aperture, so that a single cycle of any corrugation was never deformed around more than 90° of the aperture. Hence, (at small eccentricities) a limit is imposed on the lowest corrugation frequency that could be displayed, which is significant for the displays at small eccentricities. Moreover, as one moves away from the fovea, higher spatial frequencies exhibited aliasing; post-receptoral under sampling means that frequencies not actually in the stimulus are artificially created. This is also found in motion [24]. Subjects reported that they could tell that depth existed, but could not identify troughs and peaks. Pilot experiments ensured that these conditions were also omitted.

The experiment utilised a temporal 2AFC detection design, in which two stimuli were presented to subjects in random order. Both presentation times and the inter-stimulus interval were set at 500 ms. On each trial, subjects were asked to fixate the central spot and indicate in which interval the disparity modulation was present. Although this presentation time is sufficient for a saccade to be triggered, all three subjects were experienced psychophysical observers and reported that they were able to maintain fixation at all times. Two of the three subjects were naive as to the purpose of the study. For each condition there were two batches of 300 trials. A modified version of APE [25] was used to control the presentation of stimuli. A cumulative Gaussian was fitted to the psychometric function, and the 75% point was extracted. This amplitude was doubled to calculate the peak-to-trough threshold.

3. Results

Fig. 2 shows the peak to trough sensitivity as a function of corrugation frequency for annular displays with four different eccentricities. Also plotted for reference are data describing foveal disparity corrugation detection for horizontal gratings, which are taken from [11]. The data were very similar for all three observers and as a consequence have been averaged across subjects. The error bars depict the mean intra-subject error on the mean of the fitted distribution.

Sensitivity for disparity modulations was always band pass with respect to spatial frequency. However, the position of peak sensitivity shifted to lower spatial frequencies with increasing eccentricity. Optimum sensitivity changed from about 0.3 cpd at 3.5° eccentricity to about 0.06 cpd at 21.0° eccentricity. Moreover, the absolute sensitivity decreased as the stimulus moved away from the fovea. Peak sensitivity was approximately 11 arc sec (peak to trough) at 3.5° eccentricity but rose to 108 arc sec at 21°.

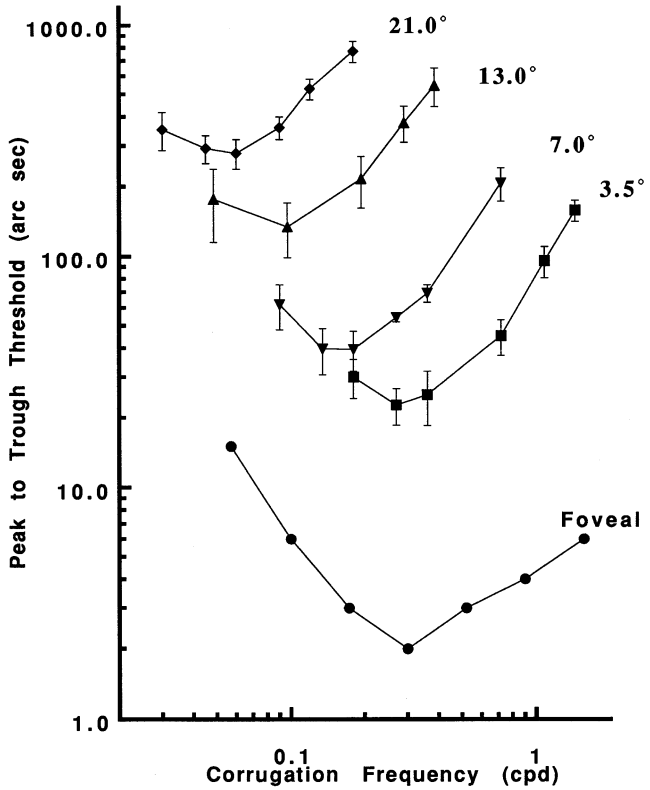

Fig. 2. Graph showing peak to trough threshold for detection of disparity modulations as a function of spatial frequency for several retinal eccentricities. Graph shows data averaged over three subjects and previous data for foveal vision obtained by Bradshaw and Rogers [11].

Subjects' verbal reports suggested that their performance was based primarily on detection of disparity corrugations at the sides of the annulus. This is probably a result of the well-known anisotropy [18]; in the fovea, horizontal corrugations are easier to detect than vertical corrugations, which would render 'horizontal' corrugations on the sides of the annulus more visible than the 'vertical' corrugations at the top and bottom. Moreover, contrast sensitivity is known to be superior on the horizontal meridian compared to on the vertical meridian for a given eccentricity [6].

4. Does the sensitivity to disparity corrugations M-Scale?

In order to compare the change in stereo-acuity with eccentricity to the change in luminance acuity, the data were replotted in terms of cycles per mm of cortex at the given eccentricity. This rescaling is based on the

estimates of the cortical magnification factor made by Rovamo and Virsu [6]. In fact, they provided slightly different scaling estimates for each visual direction. Since the stimuli were circularly symmetrical, these estimates have been averaged to provide a composite estimate of the cortical magnification factor. This can be used to convert spatial frequency into cycles per mm of cortical representation.

Fig. 3. shows the plot of peak to trough threshold as a function of spatial frequency in terms of cycles per mm of cortex, averaged over visual direction, for the same four eccentricities. It can be seen that the graphs are now aligned in a vertical direction with each showing the lowest detection threshold at 0.8 cycles per cortical mm. In other words, when the functions are approximately rescaled for cortical size, there is no variation in peak detection frequency with eccentricity[1]. The data from Bradshaw and Rogers was collected using a large field (20°) display, and hence cannot be compared with the M-scaled functions.

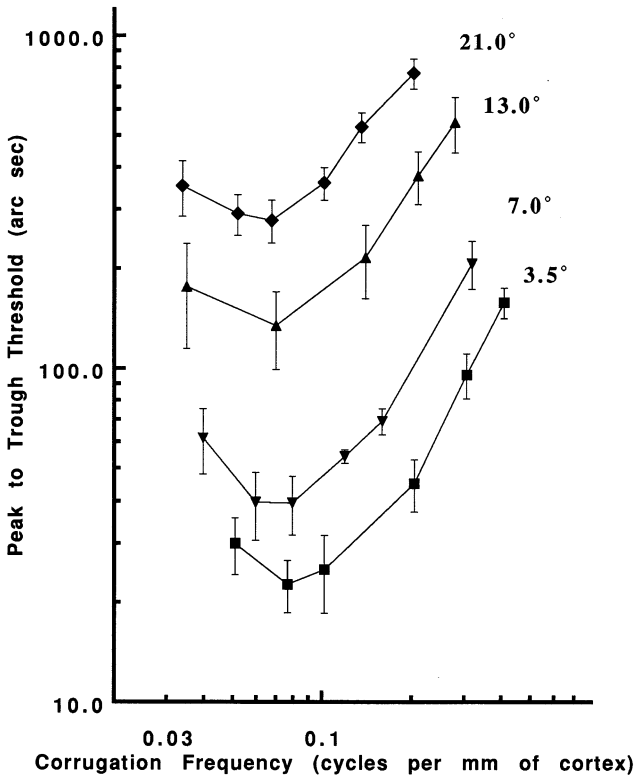

Fig. 3. Graph showing peak to trough threshold as a function of cortical spatial frequency for several eccentricities. Data are averaged over three subjects. The data from Bradshaw and Rogers [11] cannot simply be reinterpreted in this fashion, as they were measured with a large display field (20°).

[1] In contrast vision, rescaling the entire stimulus by the cortical magnification factor has the effect of making contrast sensitivity functions for different eccentricities not only become aligned, but also fit on top of one another [3]. A control experiment (data not shown) has demonstrated re-scaling annulus width in this fashion does not effect the current results in this way. A further control experiment has also shown that for the largest annulus size, presentation of the stimuli mapped onto: (i) the Vieth–Muller circle; and (ii) the empirical vertical horopter as measured by a maximum-acuity technique, produce very similar results to data presented here. We conclude that the increasing deviation from the horopter with annulus width does not underlie the results.

5. Conclusions

The analogy between brightness and depth that has been proposed by Tyler [26] for temporal disparity modulation, Tyler [7] for spatial line modulation and Tyler [9] for cyclopean corrugation [27,28] can be extended to the detection of disparity modulations in peripheral vision. This study has shown the pattern of results with disparity modulations is very similar to the pattern for detection of luminance gratings. First, the disparity modulation function is bandpass at all eccentricities. Second, all the optimal corrugation frequencies decrease with increasing eccentricity. Third, the absolute sensitivity also decreases. Fourth, the maximum corrugation frequency for which corrugations can still be seen—the cut-off point—also decreases with eccentricity.

When the sensitivity functions are re-plotted in terms of cycles per mm of cortex, it becomes clear that the shifts in the disparity modulation sensitivity as a function of eccentricity can be accounted for by the cortical magnification factor. When plotted in this fashion, it is only the absolute sensitivity of human stereopsis that increases as a function of eccentricity.

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